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Final Technical Report

Air Force Office of Scientific Research
FY 1990 University Research Initiative Program

The Structure of High Reynolds Number Turbulent Boundary Layers

by

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October 18, 1993

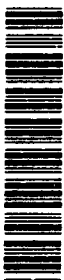
Summary

This report is the Final Technical Report for AFOSR URI Grant 90-0217. The effort described in this report is the Princeton part of a joint effort among Penn State University (Professor Jim Brasseur), Princeton University (Professor Lex Smits) and Yale University (Professor K. Sreenivasan) to try to improve our understanding of the turbulent boundary layer at high Reynolds numbers.

1. Introduction

As stated in the original proposal, some aspects of the problem that are being emphasized are: (a) the outer structure, its origin, maintenance and interaction with the small scale; (b) the role of the forcing produced by the inner structure on the stability and coherence of the outer structure, especially the way in which these latter aspects differ from those in free shear flows; (c) the development and use of new techniques in experimentation; (d) the development and use of interactive graphics-based techniques of analysis; (e) the structural relationships and relative dynamical significance of intense but infrequent events on the one hand, and small amplitude but pervasive fluctuations on the other; (f) the quantification of loosely-used concepts such as 'dynamical significance' (for example in maintaining the flow); (g) the modeling of flow dynamics by use of multifractal, wavelet, and Fourier

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analysis, and their interrelationships; (h) the understanding of the mixing and dispersion of passive scalars, especially with a view to unraveling the relationship between structures within the concentration field and those in the velocity field; (i) the effects of compressibility on several of these issues including the effects of fluid property variations; (j) the concurrent analysis of experimental and numerical data.

An important motivation for this joint effort was the realization that no single individual can possess the necessary resources or the required skills to attack this complicated problem on several interrelated fronts simultaneously, and that novel ideas and data processing tools, new perspectives and, most of all, open-minded query would be promoted by a collaboration among these three essentially independent participants, each of whom has similar but complementary interests. This, we hoped, would enable us to accomplish beyond the sum of the potential accomplishments of the individual investigators.

The crucial basis for our work was the availability of comprehensive experimental and computational data, covering as wide a Reynolds number range as possible. The high Reynolds number data that were generated under this grant are discussed in Section 2, and the low Reynolds number data are considered in Section 3. Our efforts in analyzing the data, with respect to understanding the effects of Reynolds number on the physics of the flow, are discussed in Section 4, together with implications for calculations and modelling. Some speculations on further analysis are discussed in Section 5. Two appendices are attached, one listing the original work statement, and one providing a list of publications and presentations acknowledging the support of this grant.

2. High Reynolds Number Data

In the original proposal, the highest Reynolds number case was to be obtained in the IIT facility. It became clear that the IIT facility would not be available before the end of the grant period. This was a great disappointment. Extensive inquiries were then made to collect high Reynolds number data from elsewhere to extend our data base. The final status of data collection is as follows:

(a) From the Applied Research Laboratory at Penn State, we have mean flow data at Reynolds numbers based on momentum thickness, R_θ up to 39,000. The

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only measurements in that data set are mean velocity and rms velocity fluctuation distributions. Some time-resolved data are available, but not on the Reynolds shear stress. No further measurements are planned in the near future.

(b) The experiments at Princeton have provided data at Reynolds numbers of 4,981 and 13,052, and previous work by Alving (1987) provide data at R of 5,021. These Reynolds numbers are not extraordinarily high, but all data are at two reasonably widely spaced Reynolds numbers, they are time-resolved, and spatial correlations in all three directions are available (see Table 1). Similar measurements at Yale have yielded data in the range R_θ between 1000 and 5000, thereby providing a reasonably extensive range of Reynolds numbers to establish scaling laws. The data are being analyzed, in different ways, by all three co-investigators, and the data will continue to be made available as further measurements are completed. In particular, the data collected at Princeton has been sent to Yale and Penn State for further analysis. The Ph.D. thesis of R. W. Smith (expected completion November 1993) will contain an exhaustive analysis of the Princeton data, as well as all other relevant measurements. A paper for JFM is under preparation (Smith and Smits 1993).

(c) Some progress has been made in understanding the effect of Mach number on turbulent boundary layers, and there is some hope that data taken in supersonic flows may be useful for determining Reynolds number effects. The advantage of using high speed data is that the Reynolds numbers can be very much higher than usually encountered in similar incompressible flows. Work is in progress.

(d) Some atmospheric boundary layer data have been obtained at Yale. The measurements are quite detailed, but only at one height in the atmospheric boundary layer. Some crude "visualization" experiments were also performed to understand qualitatively the nature of transport in the logarithmic region. Arrangements are underway to collect at several heights within the atmospheric boundary layer using the Rock Springs Meteorological Facility at Pennsylvania State University.

(e) Rough wall boundary layers, at wall distances large compared with a typical roughness height, approximate the infinite Reynolds number limit. At both Yale and Princeton, we are exploring the currently available data and considering the value of additional measurements rough wall boundary layers

as a potentially useful complement to our current work. Some preliminary measurements have been made at low Reynolds number in a water channel using the three-dimensional visualization tool described below in Section 3.

(f) Evidence from a number of sources suggests that, statistically, the character of the logarithmic layer of the turbulent boundary layer is very similar to homogeneous turbulent shear flow, so long as the non-dimensional shear rate and, to a weaker extent, the local Reynolds number are comparable. The implication is that the dominant dynamical features of the logarithmic layer are set by the local nondimensional shear rate and local Reynolds number rather than by the direct influence of the wall or outer boundary layer. For this reason, we have had considerable interest in the analysis of direct simulations of homogeneous shear flow in relation to the turbulent boundary layer in the high Reynolds number limit. It is our opinion that these simulations may help to understand the structure of the constant stress region (corresponding at least approximately to the region of logarithmic velocity variation), as long as the dimensionless shear rate is similar. Our analysis of the boundary layer data suggests that the approximation of the constant stress region as a region of sheared homogeneous (anisotropic) turbulence improves as the Reynolds number increases to asymptotically large values. We have performed analyses centered on careful comparisons between direct numerical simulations and experimentally obtained local statistical measures to clarify this issue, and the preliminary results were presented at the APS meeting last year (Khanna et al. 1992).

(g) Studies already completed at Penn State have focused on fundamental dynamic processes of interscale interactions in high Reynolds number turbulence. In addition to these studies, we plan to study the relationship, if any, between larger energy-containing scales and smaller dissipative scales of homogeneous turbulence with anisotropic large-scale structure similar to that encountered in the logarithmic region of the boundary layer. The focus of the work will be the role of triadic interactions in the energy transfer and coupling among scales. Preliminary work currently under way centers on the manner in which large-scale anisotropy should be specified to approximate boundary layer flows.

3. Low Reynolds Number Data

The situation with regard to low Reynolds number data appears to be very good. The work at Penn State, Princeton and Yale has converged rapidly. We now have available:

(a) A full simulation of a developing turbulent boundary layer at Reynolds numbers from 300 to about 700. This work is under way at Penn State using Spalart's new code, and it is being carried out at the NAS supercomputer facility through a grant awarded for computer time at NASA-Ames Research Center. The hydrodynamic field is now believed to be fully converged, and specific protocols relevant both to the study of the time-resolved hydrodynamic field and the passive scalar field are in progress. Of particular interest is the relationship between passive scalar and hydrodynamic field evolution when scalar is introduced at the wall and within the flow itself (see Yeung and Brasseur 1993). Recent work has also studied different representations of the data to enable direct comparisons with experimental data. Special filters designed to provide images similar to smoke or dye flow visualization look particularly promising (see Figure 1).

(b) Measurements of the full velocity field in the xy , xz and yz planes, using PIV, at Reynolds numbers of 700 and 1300, chosen to correspond (approximately) to the conditions studied in Spalart's original computations, and the new simulations at Penn State. This work is being performed at Yale in a water tunnel, and some preliminary data have been obtained. The passive scalar field in the same three planes, at the same Reynolds numbers, also being studied. The possibility of obtaining both the velocity and scalar fields simultaneously is under investigation.

(c) The full three-dimensional, time-evolving scalar field is being studied at Princeton, at the same Reynolds numbers used in the Spalart work (Re_θ of 640 and 1410). Preliminary work at a Reynolds number of 705 was completed using a smoke tunnel (Goldstein and Smits 1990 and 1994), and more recent work is concentrating on a more detailed study over a larger volume using a water tunnel, where a case with Reynolds numbers of 525 has been completed (see Delo et al. 1993). A preliminary comparison with data from the computation by Brasseur's group reveals remarkable similarities (see Figure 1).

(d) Relatively low Reynolds number time-resolved data of the passive scalar

field in the fully-developed region of the axisymmetric jet collected at Yale has been analysed at Penn State using anisotropic three-dimensional (two-space, one-time) wavelet transforms. The issue under study is the relationship between temporal and spatial scales of structural elements in the passive scalar field. In particular, because more than one spatial scale is required to define any given structural element, even in wavelet-transformed space, we are attempting to establish correlations between the temporal scale and "dominant" structural scale.

(e) Preliminary vortex dynamics calculations have already been made in collaboration with Meiburg.

4. Implications for Simulation and Modelling

A wide range of issues has been addressed using the data. Current work has already progressed on several of the following questions:

- (a) The skin friction coefficient as a function of Reynolds number. Why do the data show difference in exponent between low and high Reynolds numbers?
- (b) How do the rates of dissipation and the production of turbulence, integrated over the boundary layer, scale with Reynolds number?
- (c) How do the turbulence intensities scale with Reynolds numbers? What is the asymptotic limit?
- (d) Can the dominant dynamical features of the turbulent boundary layer be represented by eigenfunctions based on the Orr-Sommerfeld analysis of the mean velocity profile? How efficient are these eigenfunctions as basis functions for calculation?
- (e) Is there a low Reynolds number scaling for the three-dimensionality of the turbulence? Can one determine the appropriate scaling laws at low Reynolds numbers, which match with high Reynolds number behavior?
- (f) How does the extent, dynamics, and structure of the logarithmic layer depend on the Reynolds number, and how does this Reynolds number dependence affect scaling arguments?
- (g) Are the classic scaling arguments based on an inner and outer region valid over a wide range of Reynolds numbers?
- (h) What is the structure and behavior of the near-wall streaks in the limit of infinite Reynolds number? What are the implications for drag reduction, as in the case of riblets?

- (i) How closely does the constant stress region approximate a region of sheared homogeneous turbulence, and over what range of Reynolds numbers is homogeneous turbulent shear flow a useful approximation to the constant stress layer?
- (j) In a general sense, how can notions of scale similarity in the energy containing scales be used for modelling purposes?
- (k) What is the precise correlation between spatial and temporal scales? What spatial scale is correlated with what temporal scale?
- (l) Does wavelet analysis provide new insight into scale similarity?
- (m) Do wavelet transforms provide a means of identifying vortex motions in turbulent flows? Here, the full simulations of sheared homogeneous turbulence can provide valuable insight, which may lead to new interpretations of experimental turbulence data.

These studies address a wide range of interesting and possibly important questions. Different degrees of progress have been made on each of these issues. At Princeton, the publication of Smith's thesis next month will represent the most comprehensive summary of our findings. These findings, as well as additional work on the effects of Mach number are being prepared for publication as an AGARDograph, with Smits, Fernholz and Dussauge as co-authors.

5. Further Analysis

In ways that were not anticipated at the beginning of the program, a few new developments have occurred. These are briefly described below:

- (a) Probability density of velocity differences: The pdf's of velocity differences are known to be non-Gaussian and also non-symmetric. Both these aspects are related to the behavior of the tails of the distribution, and are generally equated with intermittency. (Tails = low probability, or intermittent, events.) Our recent work has shown that the asymmetry is essentially a large-scale phenomena, whereas the non-Gaussianity is due to small-scale in the sense of Fourier modes. If, on the other hand, the decomposition is made in terms of best-basis wavelet-packets, we have been able to decompose the sum total of the motion into two parts - one of which is the energy containing part and nearly completely Gaussian, the remainder

being much closer to Gaussian than the high-frequency Fourier modes.

(b) Scaling of the circulation: Another development concerns the scaling of circulation. Our experience has been that circulation around a contour which, by Stokes theorem, equals the product of the average vorticity within the contour and the area contained in the contour, scales much better than velocity differences and has nearly Gaussian pdf's - at least at the moderate Reynolds number of our measurement.

(c) Differential diffusion effects in inhomogeneous and homogeneous flows: At Yale, we have recently carried out some experiments on differential diffusion, and it seemed useful to make related studies using the numerical simulations being carried out at Penn State. While the calculations can not exactly duplicate the experiment, they will be complementary. The spreading of scalar, and its relation to the vorticity field, was part of our proposed scope.

(d) Multiplier distributions: In the logarithmic region, the scaling length is the height from the wall. As the momentum flux from a height 'h' arrives at a height 'h/2', it will have to adjust its scale accordingly. Assume that an eddy of scale 'h' splits into two sub eddies of scale 'h/2'. One can then ask what fraction of the flux goes to each of the two subeddies. Define this fraction as a multiplier. The multiplier, in general, is a random variable with a definite pdf. The pdf has been measured, and shown to possess similarity within the logarithmic region. More work is clearly required, but preliminary indications are that the scale-similarity of the Reynolds stress can be extracted completely from the multiplier distribution.

(e) Although analysis of the passive scalar field focuses on the relationship between the interpretation of passive scalar visualization in terms of the underlying hydrodynamic field, the studies are very much relevant to important issues of dispersion of contaminants and heat flux in the turbulent boundary layer. Models universally focus on global statistics of passive scalar and heat flux. Very little is known, however, of the dynamic mechanisms and temporal processes which lead to particular statistical distributions. Of particular interest here are separate influences of inhomogeneity -- the wall and outer regions of the boundary layer -- and local influences, shear and Reynolds number, which may be well-approximated by homogeneous turbulence.

(f) Fundamental issues of large-small scale interaction in high Reynolds

number turbulence are being studied as a part of this program. We have uncovered certain basic features which indicate a correlation, at some level, between large energetic scales and scales which are orders of magnitude smaller in size and lower in energy. These "distant" couplings are not necessarily predominant, but may be stimulated by sudden deviations from an equilibrium state. Further study surrounding the issue of large-small scale coupling will continue under this program.

(g) The application of closure on a "practical" level is most appropriately carried out in physical space (velocity-pressure). Basic issues of turbulence interscale dynamics at high Reynolds number, however, are often studied and modeled to great advantage in the spectral view. It is our opinion, therefore, that there is great value in establishing the relationship between turbulence dynamics in the physical space view with turbulence dynamics in the Fourier-spectral view. Significant progress has already been made in this direction, and this direction of inquiry will continue.

(h) An element in this program of research was in the development of an "analysis facility" in which quantitative measures and graphical imaging are combined for a very high level of interactive analysis of complex three-dimensional data sets. Significant strides have been made in this direction. Nearly completely implemented is a fully object-oriented "visualization system" with which the researcher may dynamically combine, and even create, quantitative analysis tools with three-dimensional graphical imaging to interrogate, analyze, and quantify complex structural and dynamical features of the turbulence data.

(i) The three-dimensional flow visualization technique has also been applied to the study of wake structures in a jet in cross-flow (Kelso et al. 1993), where it was shown that the structure proposed by Frick and Roshko (1990) is probably not correct, and that it should be replaced by a structural model using vortex loops. The method has also been used to investigate the wake behind a half-cylinder in cross-flow. Specifically, the important effects of aspect ratio were demonstrated. The experimental work was also compared to the DNS calculations by Karniadakis's group at Princeton, where similar results were obtained. Currently, the technique is being used to study the structure of the non-equilibrium turbulent flow which occurs when boundary layers enter a region of divergence.

(j) We are continuing to use wavelets in data analysis. In particular, we have used wavelet filtering of wall pressure signals to distinguish between the contributions due to shock motion and incoming turbulence (Poggie et al. 1993). This was not possible using conventional Fourier filtering. We are currently exploring the possibility of using wavelet filters as bases for ensemble averaging.

6. Final Remarks

As might be expected, the initial period of work under this program was carried out by the individual investigators with interaction predominantly through constant discussion and regular meetings. Over the past two years, however, direct interaction among the three investigators has increased monotonically, and it is our considered belief that the interactions among these investigations have fulfilled our hope that the sum of our combined efforts will be greater than the sum of our individual efforts. The initial period was a period of information exchange and individual analysis while the tools for direct collaborative protocols were being established. Specifically, the water tunnel facilities at Yale and Princeton Universities, and the boundary layer simulation at Penn State were established before data collection could begin. The protocols for collaborative data collection are now well established, and the last year of the program has focussed on data exchange, collaborative data analysis, and the increase in knowledge and understanding through the intertwining of protocols, data, and analysis. We anticipate that the collaborative nature of the studies outlined above will continue to substantially increase our knowledge in ways not possible otherwise, well beyond the grant period.

Appendix A: WORK STATEMENT

The original work statement given in the proposal is reproduced here for reference.

Penn State: J. G. Brasseur

With the aid of a graduate student, Jim Brasseur will be responsible for gathering and analyzing the numerical simulation data bases of the turbulent boundary layer, as described in Sections 7 and 8. This includes the collection, conversion, and storage of Philippe Spalart's $R_\theta = 300, 670,$ and 1410 data sets from NASA-Ames, and developing a variety of postprocessing applications for conversion of the raw data into the different physical variables which are to be explored. This also includes the modification of Spalart's code for the calculation of scalar concentrations. Jim Brasseur and Philippe Spalart have agreed on an arrangement where a graduate student from Penn State will spend a summer at the Center for Turbulence Research at NASA-Ames Research Center to carry out, under Spalart's guidance, the substantial code modifications required. Although some preliminary calculations may be carried out during the modification and testing of the code, the bulk of the concentration field simulations at $R_\theta = 1410$ will be carried out not from Penn State, but at NASA-Ames, over INTERNET. Roughly 100 Cray Y- MP CPU hours is anticipated to carry out these calculations. Jim Brasseur will be responsible for submitting a proposal to NAS (National Aerodynamic Simulation facility) at NASA-Ames for use of their Y-MP for these calculations. [Note: Because we are using Spalart's "state-of-the-art" code, the computer time required was grossly underestimated. By the end of this program, we estimate that something on the order of 800 Cray YMP hours will have been consumed, and this is with the sharing of computer resources with Joel Ferziger and Diane Bell of Stanford University.]

In order to carry out the structural analyses described in Section 8, a wide range of general-purpose graphically-based diagnostic tools must be developed within the 'Postprocessing and 3D Graphical Imaging Laboratory' described in Section 7.2. Included in this process must be the development of interfaces and applications which allow for the manipulation of graphical objects on the screen, while at the same time accessing the data sets through a variety of numerical applications. In addition to these general-purpose tools

special-purpose applications must be designed specific to the analyses described in Sections 8 and 9. Jim Brasseur will be responsible for these developments. Support has been requested for a 'Software Engineer' whose main effort will be the development of these graphically-based tools and interfaces. These will be developed in collaboration with Ardent Computer. Jim Brasseur has reached an agreement with Bruce Bordon, VP of Strategic Planning at Ardent Computers, whereby Ardent will train our Software Engineer at their facility on the West Coast for as long as three months, and will pay him a salary during this period sufficient to cover his living expenses and will continue work closely with us in the development of the graphical applications. The level of collaboration with Ardent Computers in this endeavor will likely increase as the program proceeds. It should be emphasized that, whereas the primary hardware components are in place, the development a facility in which different researchers could bring their data for analysis using

g specially designed analytical tools is a non-trivial and long-term effort. Through this facility, the researchers in this program will have the capability to work jointly in the integrated analysis of experimental with numerical data.

[Note: unfortunately, the anticipated collaboration with Ardent, now Stardent computers, did not materialize, primarily because of difficulties within Stardent computers. Nevertheless, we have made great strides in the development of an "analysis facility" centered on a novel visualization system specially designed for the analysis of turbulence data.]

Much of the structural analysis of the boundary layer data described in Section 8 will be carried out by a Ph.D. student under the direction of Jim Brasseur. The interrelationships between numerical and experimental data, and calculations of fractal structure, will be carried out in collaboration with Smits, Sreenivasan, and their students. The study of the interrelationships among the Fourier, wavelet, and physical space descriptions, described in Section 9 will also be the responsibility of Jim Brasseur in collaboration with Sreenivasan. Jim Brasseur, with the aid of his second student, will develop a spectral code for this analysis, as described in Section 9. Calculations of spectral development and its relationship to physical structures will be studied in detail at Penn State. The wavelet decomposition will be applied and studied in collaboration with Sreenivasan at Yale. In all analyses, considerable exchanges of data, information, knowledge, and insights will take place among

the three primary investigators and their research groups.

Princeton: A. J. Smits

The current program at Princeton, funded by AFOSR, is directed at a study of the detailed structure of supersonic turbulent boundary layers. The experiments are designed to elucidate physical models and mechanisms that are particular to compressible turbulence, such as the effects of compressibility on the nature of the large-scale motions, the scaling laws for high Reynolds number supersonic turbulent flows, direct compressibility effects that cause the exchange of turbulence energy among the vorticity, entropy and sound modes, the transport of heat and momentum by compressible turbulent motions, and the interaction of turbulence with a shock wave.

The study proposed here will expand on the existing experimental program to focus on some particular aspects of turbulence in compressible flows, especially the question of developing a model for the evolution of the large scale motions in flows with compressibility, at high Reynolds numbers. There are several parts to this problem, the first part being able to distinguish between the scalar and vorticity interfaces: there is no reason to suppose they are identical, although the high correlation between u' and T' seems to suggest a strong relationship. Secondly, there is the problem of scaling the coherent motions such that we can separate Reynolds number and Mach number effects, which means essentially that we must identify the role of fluid property variations. This scaling study can only consider the behavior of the larger-scale motions since in typical compressible flows the motions directly affected by viscosity are far too small to be observed (for the flow given in figure 10, for instance, the viscous length ν/u_τ is less than $2.2 \mu\text{m}$ everywhere in the flow field).

The principal experimental means for these investigations of supersonic flows are the Rayleigh scattering and line-marking techniques developed by Miles et al. (1989) at Princeton. Past progress in the study of high Reynolds number compressible flows has been hampered by the difficulty of obtaining sufficient information on the space and time distribution of the fluctuating density and velocity field. LDV systems and hot-wire anemometers only provide single-point information, and time-histories of fluctuating quantities, which permit the study of instantaneous structure, have only recently become

available (Spina and Smits, 1987). However, the recent development of new optical diagnostic techniques by R. Miles will allow instantaneous two-dimensional density cross sections in supersonic flow fields to be obtained using Rayleigh scattering, and permit the generation of time lines in supersonic air flows, thereby simultaneously giving instantaneous velocity profile information. The images of the density field have already provided new insight into the structure of high speed boundary layers (Smith, Smits & Miles 1989). When combined with the line marking technique, we will have the first opportunity to directly observe the coupling between velocity and density fields in a wide variety of flows, thereby making a major contribution to fulfilling the aims of the proposed research. To expand the scope of the current effort, funds are requested to help support a post-doctoral research associate. Smits's graduate student Mike Smith has been a major contributor to the successes achieved so far, and he has shown interest in continuing as a post-doc. We feel that the presence of a post-doctoral research person will make it possible to obtain the data sets which are to be analysed at Yale and Penn State as quickly as possible.

We intend to analyze these data in close cooperation with the groups at Yale and Penn State. In particular, we will explore the use of multi-fractals to derive scaling information for events of dynamical significance, and we expect to involve Sreenivasan and Brasseur in this endeavor. Sreenivasan is already applying fractal analysis to the Rayleigh scattering images obtained in preliminary work, and we expect that some comparisons between subsonic and supersonic flows may be completed as early as this spring. We intend to extend these interactions under the current proposal to include direct involvement of graduate students from Princeton, Yale and Penn State in the activities at each of the other institutions.

In additional experiments proposed here, we intend to try and obtain double-pulsed images of the density field to study the evolution of the larger scales in time. In previous work, Smith and Smits (1988) obtained high speed schlieren movies of a Mach 3 boundary layer to show the convection of large-scale motions inclined at about 45 degrees. However, the schlieren method depends on the second derivative of the density, and it integrates across the optical path, and details of the motions are completely obscured. In contrast, double-pulsed Rayleigh images will show the evolution of the density (directly)

in a plane, and they can be compared directly with similar images obtained by numerical simulations and flow visualizations at lower Mach and Reynolds numbers. We believe that these time-evolving images are crucial for the development of dynamically accurate models. This work will require the technical support of the Applied Physics Laboratory headed by Prof. Miles, and the Princeton budget contains a line item for the support by Dr. Walter Lempert from the Applied Physics Laboratory. In preliminary work, we intend to use existing laser equipment to study the feasibility of this method. In later work, a new YAG laser will be required, and we intend to obtain this equipment through supplemental proposals to AFOSR or NSF. The services of Dr. Lempert will also provide additional support for the diagnostic activities of the Gasdynamics Lab. This support is extremely valuable in terms of efficient usage of the sophisticated laser and optical techniques proposed here, and his financial support is seen as a high-priority budget item.

At Princeton, we are also actively investigating the structure of incompressible boundary layers over a wide range of Reynolds numbers, to develop a better understanding of the role of Reynolds number in the compressible case. Four flows are being considered: two Mach 3 boundary layers, one with $R_\theta = 15,000$, the other with $R_\theta = 80,000$ (based on freestream conditions), and two subsonic boundary layers, one with $R_\theta = 15,000$ (to match the supersonic case), the other with $R_\theta = 1410$ (to match the Direct Numerical Simulations by Spalart (1988)). In the supersonic flows, the primary experimental tools are the Rayleigh scattering and RELIEF techniques already described. In the subsonic flows, we are adapting the scanning laser sheet technique developed by Nosenchuck and Lynch (1986) whereby three-dimensional images of dye flow visualization in water were constructed using a scanning laser sheet. As the sheet rapidly scans through the flow, the two-dimensional image obtained at each height is recorded on videotape. The image sequence is digitized, and reconstructed using image processing to reveal the fully three-dimensional motions. Nosenchuck and Lynch used this technique to study a turbulent spot, and Sabadell, Watmuff and Smits (1989) have used it to examine the structure of non-Newtonian boundary layers.

We are currently using this visualization technique in the lowest Reynolds number case suggested above ($R_\theta = 1410$), using smoke as the scattering medium. We are using a 20W copper vapor laser pulsing at 12 kHz,

in combination with a high-speed movie camera, to record from 24 to 120 image planes (total scan time 2 msec to 10 msec). The images will then be digitized, and reconstructed using the software developed by Russell and Miles (1987). We intend to obtain successive images in time to follow the three-dimensional motions over some length of time to examine their development. These data will be made available to Sreenivasan and Brass for further detailed analysis. We expect that the 3D graphical imaging facility at Penn State will be especially important because of its ability to handle large blocks of three-dimensional time-dependent data. In additional experimental work, we propose to perform similar visualizations for the $Re_\theta = 670$ case, enabling further comparisons with the computations by Spalart, and Robinson et al. (1988), and the additional calculations and analysis proposed by Brasseur (Section 7.3). It will be particularly interesting to examine the usefulness of fractal geometry in describing scaling laws, entrainment processes, and to extend the fractal analysis of two-dimensional geometries (cross-sections) to three-dimensional geometries (volume-filling data), using the scanning laser sheet experiments.

We also propose to perform extensive boundary layer surveys of the more conventional type in the highest Reynolds number incompressible case attainable at Princeton. These will serve as a basis for comparison for the proposed measurements in the IIT facility at even higher Reynolds numbers. One advantage of the Princeton tunnel is that high-accuracy dynamic calibration techniques will be used to generate the best possible data set.

Yale: K. R. Sreenivasan

Sreenivasan will be responsible for negotiating with Professor H. M. Nagib at IIT the scheduling of high Reynolds number experiments. This will be done at a time that is mutually convenient to the parties involved. The proposal would be to document, as Klebanoff (1954) did about thirty-five years ago, a high Reynolds number turbulent boundary layer. The point of departure will be that advanced instrumentation has become available since Klebanoff's days, new ideas (some of which are discussed above) are now ready for exploitation, and that a high-quality facility will shortly be available. All data acquired will be accessible to any one in the community wishing to make use of them. It is proposed that one student of Sreenivasan and another of Smits will spend some

months of their time at IIT, and work with the local people there. Both Sreenivasan and Smits will make periodic trips to IIT to facilitate this work. Long before this collaboration with Smits was conceived, Sreenivasan had informally discussed such a possibility with Professor Nagib, who views it very favorably. It is our belief that we shall not be needing extensive financial support for this effort. The graduate students will have been paid already, and we are intending to use some of the IIT equipment and, if necessary, as much of the Yale and Princeton equipment as can be comfortably moved. Of course, all this will have to be negotiated in specific terms; we shall do this as soon as possible.

Sreenivasan will also be responsible for the vortex dynamic calculations. Meiburg and Sreenivasan have discussed this project, and Meiburg has made some preliminary calculations. This problem forms the core of Meiburg's interests, and we expect to have him do the bulk of the necessary calculations. To make matters simple, he will be treated as a consultant and his efforts will be compensated for by a part of the summer or academic salary.

The multifractal analysis will be done primarily at Yale, but some analysis on the numerical obtained data will be done at Penn State. Preliminary analysis will be done on the moderate Reynolds number data we can acquire in the Yale wind tunnel where boundary layers with momentum thickness Reynolds numbers of the order of 4000 can be attained without much problem. Later, we hope to use the high Reynolds number data to be acquired at IIT. We also plan to use the Princeton data obtained in supersonic boundary layers not only for the multifractal analysis but also for the fractal dimension estimates of the interface, etc. Since we have shown elsewhere (Sreenivasan et al. 1989) the connections between mixing and the fractal and multifractal aspects of a turbulent flow, we shall be interpreting the outcome in those terms. Similarly, simple binomial models of the type described earlier for energy dissipation (Meneveau & Sreenivasan 1987b) will be constructed for momentum transfer towards the wall. As already mentioned in Section 3, we shall also evaluate whether the large intensity events occurring near the wall are as important as generally believed in terms of the Reynolds stress containing motion, or whether the so-called 'background turbulence' plays a significant role.

The basic tool is the ϵ -filter' (a term we just invented in the context of

multifractals); neither the idea nor its applications have been discussed before, but the basis can be found in Sreenivasan & Meneveau (1988) where it was shown that all the dissipation at infinitely large Reynolds number occurs on a fractal set of $\alpha = 0.87$. The formalism has already been tested (in a preliminary way) for the energy dissipation and the results are surprising: nearly all the energy dissipation at high Reynolds number comes from pervasive small amplitude fluctuations rather than large amplitude events. The latter may still be essential in other contexts.

The wavelet analysis is primarily the responsibility of Sreenivasan; here as in other aspects, data may be generated locally at Yale and Princeton or obtained from elsewhere, and similar analysis on the numerical generated data will be done at Penn State. As already mentioned, these ideas can be used for rational derivations of various conditional schemes of prevalence in the literature.

Finally, Sreenivasan also intends to obtain simultaneous and quantitative field measurements of a passive scalar in the boundary layer. We have already established that the technique works in free shear flows, and have obtained useful data in those flows. The boundary layer is a somewhat different animal, and therefore requires additional work. Since we are already in the middle of measurements in free shear flows, we believe that the boundary layer measurements will not be time consuming. Attempts will be made to study flows at $R_\theta = 670$ and 1410 corresponding to Spalart's simulations, so that concurrent analysis of experimental and numerical data can be performed. The basic equipment and expertise is already available. Further, we do not need much financial support for this work since it forms a part of our current work partly supported by AFOSR. Perhaps a few miscellaneous laboratory supplies, especially of the optical variety, might be all that is needed. Apart from the data processing that will be done at Yale, these data will be made available to Jim Brasseur at Penn State for the analysis described elsewhere (Section 9).

Appendix B: Publications Acknowledging This Grant

Delo, C. and Smits, A.J., "Three-Dimensional, Time-Resolved Visualization of a Low Reynolds Number Turbulent Boundary Layer." Proceedings Eleventh Australasian Fluid Mechanics Conference, Univ. of Tasmania, Hobart, Australia, December 14-18, 1992.

Delo, C. and Smits, A.J., "Visualization of the Three-Dimensional, Time-Evolving Scalar Concentration Field in a Low Reynolds Number Turbulent Boundary Layer." Proceedings International Conference on Near-Wall Turbulent Flows, Tempe, Arizona, March 15-17, 1993. Published by Elsevier, 1993.

Goldstein, J.E. and Smits, A.J., "Volumetric Visualization of a Low Reynolds Number Turbulent Boundary Layer," Paper #GA6, 43rd Annual Meeting, Division of Fluid Dynamics, American Physical Society, November 1990.

Goldstein, J. and Smits, A.J., "Flow Visualization of the Three-Dimensional, Time-Evolving Structure of a Turbulent Boundary Layer." To appear Physics of Fluids A, February 1994.

Kelso, R.M., Delo, C. and Smits, A.J. (1993) "Unsteady Wake Structures in Transverse Jets," Proc. AGARD Symp. Computational and Experimental Assessment of Jets in Cross Flow, Winchester, UK, April 19-22.

Khanna, S., Smith, R.W., Basseur, J.G., Smits, A.J. and Sreenivasan, K.R., "Comparison of the Inertial Region of a High Reynolds Number Turbulent Boundary Layer With Homogeneous Shear Flow." Paper #DA7, 45th Meeting of the American Physical Society Division of Fluid Dynamics, Tallahassee, Florida, November 22-24, 1992.

Poggie, J., Smith, D.R. and Smits, A.J., "Quantitative Analysis of Rayleigh Scattering Images of a Supersonic Boundary Layer by Means of Digital Image Processing," Paper #IA5, 43rd Annual Meeting, Division of Fluid Dynamics, American Physical Society, November 1990.

Poggie, J. and Smits, A.J., "Mixing Enhancement in a Compressible Turbulent Shear Layer." Paper #CB7, 44th Meeting of the American Physical Society Division of Fluid Dynamics, Tempe, Arizona, November 24-26, 1991.

Poggie, J., Smits, A.J. and Glezer, A., "The Dynamics and Control of Fluctuating Pressure Loads in the Reattachment Region of a Supersonic Free Shear Layer," AIAA Paper #92-0178, AIAA 30th Aerospace Sciences Meeting, Reno, Nevada, January 1992.

Poggie, J. and Smits, A.J., "Control of Pressure Fluctuations in the Reattachment Region of a Supersonic Shear Layer," AIAA Paper #93-0385, AIAA 30th Aerospace Sciences Meeting, Reno, Nevada, January 1993.

Poggie, J. and Smits, A.J., "Application of Wavelets to the Analysis of Single-Point Turbulence Data," To appear Proceedings of Meeting on Multiscale Stochastic Processes Analyzed Using Multifractals and Wavelets, University of Cambridge, March 29-31, 1993.

Poggie, J. and Smits, A.J., "Control of Pressure Fluctuations in the Reattachment Region of a Supersonic Shear Layer," AIAA Paper #93-3248, AIAA 3rd Shear Flow Control Conference, Orlando, Florida, July 7-9, 1993.

Smith, R.W., "The Effects of Reynolds Number on Turbulent Boundary Layer Behavior." Ph.D. Thesis, Department of Mechanical and Aerospace Engineering, Princeton University, 1993.

Smith, R.W. and Smits, A.J., "Effect of Reynolds Number on the Large Structure of Turbulent Boundary Layers," AIAA Paper #91-0526, AIAA 29th Aerospace Sciences Meeting, Reno, Nevada, January 1991.

Smith, R.W. and Smits, A.J., "A Preliminary Model for the Effect of Reynolds Number and Mach Number on the Large Scale Structure of Turbulent Boundary Layers," Proc. Boundary Layer Workshop, NASA Langley Research Center, Hampton VA, August 1990.

Smith, R.W. and Smits, A.J., "Prediction and Measurement of the Decay Rate of Large Scale Structures in Turbulent Boundary Layers," Paper #IA2, 43rd Annual Meeting, Division of Fluid Dynamics, American Physical Society, November 1990.

Smith, R.W. and Smits, A.J., "Scale Dependency of Convection Velocity and Structure Angle in a Turbulent Boundary Layer." Paper #IB1, 44th Meeting of the American Physical Society Division of Fluid Dynamics, Tempe, Arizona, November 24-26, 1991.

Smith, R.W. and Smits, A.J., "High Reynolds Number Turbulence." Paper #HA8, 45th Meeting of the American Physical Society Division of Fluid Dynamics, Tallahassee, Florida, November 22-24, 1992.

Smith, R.W., Poddar, K. and Smits A.J., "Application of the Wavelet Transform to the Analysis of Turbulent Flows," Proceedings USA-French Workshop "Wavelets and Turbulence," Princeton NJ, June 3-7, 1991. To appear Springer Verlag.

Smith, R.W. and Smits, A.J., "The Effects of Reynolds Number on Turbulent Boundary Layer behavior." Under preparation for JFM, 1993.

Smits, A.J., "New Developments in the Understanding of Supersonic Turbulent Boundary Layer Structure", Proc. Twelfth Symposium on Turbulence, University of Missouri-Rolla, Rolla, Missouri, October 17-19, 1990.

Smits, A.J., "Structure of Supersonic Boundary Layers", AFOSR Contractors Meeting on Turbulence Research, Ohio State University, Columbus, Ohio, April 1-3, 1991.

Smits, A.J., "Turbulent Boundary Layer Structure in Supersonic Flow." Philosophical Transactions of the Royal Society A, Vol. 336 pp. 81-93, 1991.

Spina, E.F., Robinson, S.K. and Smits, A.J., "The Physics of Supersonic

Turbulent Boundary Layers." To appear Annual Review of Fluid Mechanics, Vol. 26, 1994.

Wang, Q., Brasseur, J.G., Smith, R.W. and Smits A.J., " Application of Multi-Dimensional Wavelet Transforms to the Analysis of Turbulence Data," Proceedings USA-French Workshop "Wavelets and Turbulence," Princeton NJ, June 3-7, 1991. To appear, Springer-Verlag.

Type of survey	Re_θ	Used for ...	f_s (Hz)	T (sec)	Filtering band (Hz)	l (mm)	l/d	l^+
Single-point hot-wire surveys								
Normal-wire ⁻¹ (u')	4,981	Statistics	2,500	65.5	0-25,000	.75	148	57
		Energy spectra	50,000	5.2	0-25,000	.75	148	57
Crossed-wire ⁻¹ (u',v')		Statistics	2,500	65.5	0-25,000	.75	148	57
		Energy spectra	50,000	3.3	0-25,000	.75	148	57
Crossed-wire ⁻¹ (u',w')		Statistics	2,500	65.5	0-25,000	.75	148	57
		Energy spectra	50,000	3.3	0-25,000	.75	148	57
Normal-wire (u')	5,021	Statistics, Energy spectra	50,000	13.1	0-25,000	.79	156	62
Normal-wire (u')	13,052		50,000	15.7	0-25,000	.81	159	60
			50,000	19.7	0-25,000	.79	156	59
Crossed-wire (u',v')			50,000	9.8/6.6 [†]	0-25,000	.91	179	68
Crossed-wire (u',w')			50,000	9.8/6.6 [†]	0-25,000	.91	179	68
Multiple-point normal-wire surveys								
Streamwise separations	5,021	$R_{11}(x, 0, 0, t)$	50,000	16.4	0-25,000	.84	165	66
	13,052		50,000	16.4	0-25,000	.87	172	65
Wall-normal separations ⁻¹	4,981	$R_{11}(0, y, 0, t)$	250,000	1.97	10-400,000	.75	148	57
Wall-normal separations	13,052		250,000	1.97	0-25,000	.75	148	56
Spanwise separations	4,981	$R_{11}(0, 0, z, t)$	250,000	2.62	10-125,000	.75	148	57
	5,021		250,000	1.97	0-25,000	.85	167	67
	13,052		250,000	1.97	0-25,000	.75	148	56

Table 1. High Reynolds number data collected at Princeton (Smith, 1993).



Figure 1a. Side view of DNS data, filtered to resemble passive scalar distribution, at a Reynolds number of 523. Flow is from left to right (Brasseur and Moquin 1993).



Figure 1b. Plan view of DNS data, filtered to resemble passive scalar distribution, at a Reynolds number of 523. Flow is from left to right. Data at $y^+ = 225$, $y/\delta = 0.94$ (Brasseur and Moquin 1993).



Figure 1c. Two-dimensional images obtained in the water channel at a Reynolds number of 550. The flow is from left to right, and the field of view is about 4.8×2.4 boundary layer thicknesses. Image data (enhanced to use all grey values) at $y^+ = 250$, $y/\delta = 0.85$ (Delo et al. 1993).